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STUDY OF STATISTICAL CHARACTERISTICS OF SEA WAVE SLOPES ACCORDING TO CHARTS OF WAVE STEREOPHOTOGRAPHY

L. M. Martsinkevich

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16. Abstract

The statistical characteristics of the slopes of waves are calculated on the basis of charts of wave stereophotography. It is shown that the distribution of the projections of slope onto the main axis of wave propagation and onto the axis perpendicular to it obey a normal distribution law. The distribution of slopes corresponds to the theoretical law of distribution, derived previously.

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STUDY OF STATISTICAL CHARACTERISTICS OF SEA WAVE SLOPES ACCORDING TO CHARTS OF WAVE STEREOPHOTOGRAPHY

L. M. Martsinkevich

The main purpose of experimental investigation of the slopes of sea waves /83* by various authors was primarily investigation of the distribution of the projections of slope onto two mutually perpendicular axes: one coinciding with the direction of the wind (waves) and one perpendicular to it.

Analysis of experimental data showed that the distribution of slope projections in the first approximation obeys a normal law.

Small, but systematic deviations of the experimental distributions from the normal law were observed by Cox and Munk [6] during observations on the open sea, by Schooley in laboratory tests [9], and by V. F. Tsyplukhin during measurement in coastal waters [5].

On the other hand no such deviations were observed by Schooley [10] (during measurements on a river surface), by M. S. Lonquet-Higgins, D. E. Cartwright and N. D. Smith [8] (measurements using buoys in the open sea), Duntly [7] (electrical measurements on a lake) and Yu. G. Burtsev [1] (who took time exposures of flickers of artificial light on a wavy sea surface).

The discrepancy of the conclusions of the various authors on this subject, the sparsity of observations, on the basis of which these conclusions were made, and also the fact that many of the measurements pertain to the high--frequency spectrum of wave action, make it essential to check the hypothesis of normal distribution of slope projections against the voluminous experimental data on the lower-frequency spectrum of wave action.

A decision was made to check the correspondence of the distribution of slope projections to the normal law, using charts of wave stereophotography, to which Soyuzmorniiproyekt [State Planning, Design and Scientific Research Institute of Marine Transportation of the Ministry of the Maritime Fleet, USSR] had access. The data that were used were obtained from serial aerial

*Numbers in the margin indicate pagination in the foreign text.

photography of sea waves, conducted at sea in the winter of 1964 under conditions where the wave action corresponded to deep water conditions. The wind velocity varied from 10 to 15 m/s and wave height varied from 0.64 to 2.3 m. The character of wave action also varied: from irregular three-dimensional waves to formations approaching wave ridges, indicating the nearness of the character of the wave action to two-dimensional.

Stereophotographs of the waves were taken with two synchronous aerial cameras, installed on the wings of the aircraft. Type AFA-37 cameras with a focal length of 70 mm were used. The photography base was 24.3 m; the altitude was 140-180 m. Photography was done in series at one frame every 5 seconds [2]. The isolines of the relief of wind-induced waves were plotted on a STD-2 topographic stereometer; the isolines were plotted in 0.5 m intervals.

The data from five series of observations, two of which were conducted on 6 February 1964 and the others on 4, 10 and 12 February, were used for processing. Since the distribution of slope projections onto the principal axis of wave propagation and on the axis perpendicular to it was investigated for each /84
series, a total of 10 statistical sets was examined. The volume of the statistical data, obtained as a result of processing, was 22,000 pairs of sampled slope projections.

Processing of the charts for the purpose of determining the slopes of sea waves was never done previously. Therefore a method of such processing was developed first.

Slope is represented on the plane of the chart as a vector of length α (magnitude of slope) and direction Θ, measured from the X axis, directed for convenience along the principal axis of wave propagation.

The projections of slope onto the principal and perpendicular axes of wave propagation, representing the derivatives of elevation in terms of the given axes (ξ_1 and ξ_2, respectively), were computed as the differences of the relief marks on the chart at the ends of a 10-meter spatial interval in terms of the length of this interval:

$$\xi_1 = \frac{\Delta\zeta}{\Delta x} = \frac{\zeta_3 - \zeta_4}{\Delta x}; \qquad (1)$$

$$\xi_2 = \frac{\Delta\zeta}{\Delta y} = \frac{\zeta_3 - \zeta_1}{\Delta y}. \tag{2}$$

Here ζ_2 and ζ_4 are the relief marks of the wavy sea in the direction of the X axis; ζ_1 and ζ_3 are the relief marks in the direction of the Y axis; Δx and Δy are the steps on the X and Y axes, respectively.

The studies revealed that the 10-meter interval is quite sufficient for transmitting the behavior of slope along a given cross section of the chart. Breaking up of this interval would have led inevitably to unjustified interpolation and rough extrapolation, particularly in small-gradient ranges, to which correspond extremely rare isohypses on the chart.

Although the 10-meter interval was sufficient for transmitting the character of change of the relief of wavy sea in the form in which it is depicted on the plane of the chart, it of course is not sufficiently small for transmitting the dynamics of the true slopes of the sea surface, in other words certain average slope projections are taken from the charts.

Since the purpose of the study was not only to determine slope projections but also the magnitudes of slope, it was necessary to have pairs of slope projections pertaining to the same point. Therefore the ζ values used for computing the slope projections were taken from points on the chart located at the nodes of a 5-meter square grid. The grid was superimposed on a transparent measuring grid, which was arranged on the plane of the chart in such a way that the lines forming the grid were oriented along the principal wave propagation axis and the axis perpendicular to it.

The projection of slope onto the main wave propagation axis ξ_1 was assumed positive in the case of increasing ζ in the direction of wave propagation and negative in the opposite case; the projection of slope onto the axis perpendicular to the principal axis ξ_2 was assumed positive in the case of increasing ζ to the right from the axis of wave propagation.

The magnitudes of the slopes themselves were calculated in accordance with the equation

$$\alpha = \sqrt{\left(\frac{\Delta\zeta}{\Delta x}\right)^2 + \left(\frac{\Delta\zeta}{\Delta y}\right)}\,. \tag{3}$$

After ξ_1, ξ_2 and α were computed their statistical distribution and the dispersions of the slope projections and average magnitudes of slope were computed for each statistical set. The results are presented in Table 1. To these data correspond information on wind velocity V, average heights of wave oscillations $\bar{h}$, heights of three-dimensional waves h_1 and average wavelengths $\bar{\lambda}$.

TABLE 1

Series No.	V, m/s	Wind direction, deg	$\bar{h}$	$\bar{h}_1$	$\bar{\lambda}$	No. of sampled values n	$\sigma^2_{\xi_1}$	$\sigma^2_{\xi_2}$	$\bar{\alpha}$
1	11	170	0,5	0.64	33	2300	0,00075	0,00039	0,026
2	12	210	1,1	1,4	41	8223	0,00250	0,00096	0,043
3	13	200	1.3	1,75	45	1239	0,00330	0,00110	0,0[illegible]6
4	12	220	1,4	1,8	52	2174	0,00324	0,00156	0,059
5	15	190	1,8	2.3	61	7716	0,00363	0,00175	0,061

Commas indicate decimal points.

So-called "probability paper," on which the curve of normal distribution traced on it is a straight line [4], was used for checking the correspondence between the distribution of slope projections and the normal law. This probability paper is shown in Figure 1a. The statistical integral probabilities are presented in Figure 1a for five statistical sets. It is easy to see that the integral probabilities of the slope projections for all five cases are grouped around the straight line.

Thus, the distribution of slope projections onto the principal axis of wave propagation and the axis perpendicular to it may be considered normal.

We will now investigate the statistical distribution of slopes. We will assume that the distribution of statistical probabilities is described by the integral distribution function of standard slopes $\alpha/\bar{\alpha}$, derived previously [3] and written in the form: /85

$$F\left(\frac{\alpha}{\bar{\alpha}}\right) = 1,616 \int_0^{\frac{\alpha}{\bar{\alpha}}} \frac{\alpha}{\bar{\alpha}} \exp\left[-0.838\left(\frac{\alpha}{\bar{\alpha}}\right)^2\right] I_0\left[0,228\left(\frac{\alpha}{\bar{\alpha}}\right)^2\right] d\left(\frac{\alpha}{\bar{\alpha}}\right). \quad (4)$$

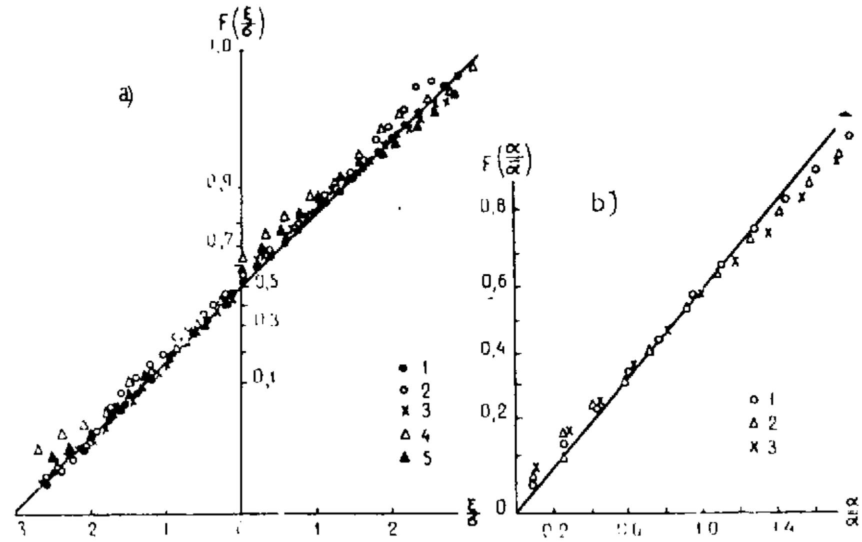

Figure 1. Integral Distribution of Statistical Slope Characteristics (According to Results of Processing of Charts of Wave Stereophotography): a) Integral distribution of slope projections: 1) ζ_1 (n = 2,174); 2) ζ_1 (n = 1,239; 3) ζ_1 (n = 7,716); 4) ζ_2 (n = 1,239); 5) ζ_2 (n = 2,174); b) Integral distribution of slopes: 1) n = 2,174; $\bar{\alpha}$ = 0.059; 2) n = 7,716, $\bar{\alpha}$ = 0.061; 3) n = 1,239, $\bar{\alpha}$ = 0.056.

To check the correspondence between the statistical distribution of the slopes and distribution (4) the standard slopes $\alpha/\bar{\alpha}$ were plotted on the abscissa axis and the scale of integral probabilities was transformed so that the theoretical distribution curve became a straight line.

For this purpose a straight line was constructed at an arbitrary angle from the coordinate origin and the scale was marked off as follows. Going up from the fixed argument $\alpha/\bar{\alpha}$ on the vertical to the straight line, and then moving parallel to the abscissa axis to the intersection with the ordinate axis, we write on it the theoretical integral probability that corresponds to this value of the argument. /86

Then, using the scale thus obtained, we write the statistical integral probabilities on the chart. In the case when the statistical distribution corresponds to the given theoretical law the points should lie on a straight line.

The statistical integral probabilities are shown in Figure 1b for three statistical sets of slopes. The figure shows that the integral probabilities of the slopes are grouped rather compactly for all cases along the straight line.

It may therefore be assumed that the slope distributions obey the law described by function (4).

Such are the results of experimental investigation of the distribution of projections and slopes according to wave stereophotographic charts.

In conclusion the author takes this opportunity to acknowledge Yu. M. Krylov for his valuable advice and for graciously providing wave stereophotographic materials.

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